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FATIGUE DESIGN OF WELDED STAINLESS STEELS

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Abstract. Stainless steels are widely used in the chemical processing and power generation industries. They are, however, increasingly being considered for structural applications in, for example, construction and transportation industries, where they offer the advantage, over conventional structural steels, that painting or other corrosion protection is not necessary. This is especially true for duplex stainless steel (ferrite and austenite), which offers the advantage of high strength and lower costs over the austenitic stainless steels. Many applications in the chemical, power generating and structural areas mean that welded components and structures experience fatigue loading. However, there are remarkably few published fatigue data for welded joints in stainless steels, especially duplex.

Fatigue test results obtained from four fillet welded joints are presented and evaluated in comparison with available published data, for the same details in C-Mn steels and current design S-N curves. In the basis of this research, fatigue design curves for these types of joints in stainless steels are proposed.

1. INTRODUCTION

Stainless steels are widely used in the chemical processing and power generation industries. However, increasingly they are also being considered for structural applications in, for example, construction and transportation industries, where they offer the advantage over conventional structural steels that painting or other corrosion protection is not necessary (1). This is especially true of duplex stainless steels (ferrite plus austenite), which offers the advantage of high strength and lower cost over the austenitic stainless steels. Many applications in the chemical, generating and structural areas mean that welded components and structural experience fatigue loading. However, there are remarkably few published fatigue data for welded joints in stainless steels, especially duplex (2-5). Thus, published information is of little direct value to the designer of a fatigue-loaded stainless steel component or structure.

In the light of this situation, a major project is being funded by ECSC (3). It involves study of the fatigue performance of welded austenitic and duplex stainless steels, with the aim of providing fatigue design guidance and understanding any differences between their behaviour and that of welded carbon manganese steels (C-Mn). Basic fatigue design data are readily available for welded joints in such steels (e.g. Eurocode 3, IIW), and it was hoped that data for stainless steels could be incorporated in the same framework. Particular attention is given to the load carrying cruciform joints with total or partial lack of penetration, where fatigue cracking usually starts at the weld root. These joints show the lowest fatigue strength, and therefore deserve a more detailed analysis in the fatigue design process.

The present paper presents both fatigue endurance data for the weld details being studied, and a FE analysis of crack propagation from the weld root of the load carrying cruciform joints.

2. EXPERIMENTAL DETAILS

The test specimens were manufactured for 10 mm thick stainless steel rolled plates to ASTM A240-95 304L (austenitic) and S31807 (HYPERESIST 2205 Duplex), supplied by Avesta, Sheffield. Their properties are given in Table 1.

Table 1. Material Properties

a) Chemical Analysis

Steel Type	Cast nr.	Element % by weight			
		C	Si	Mn	P
304L	C1313	0.017	0.50	1.41	0.020
S31803	C1425	0.017	0.41	0.85	0.018

Element % by weight				
S	Cr	Mo	Ni	N
0.001	18.40	-----	10.14	0.035
0.001	22.53	3.17	5.97	0.162

b) Tensile Properties

Steel Type	Proof strength, N/mm^2		UTS, N/mm^2	Elongation %
	0.2%	1%		
304L	237	293	582	57
S31803	527	653	797	34

Fatigue tests were performed on the weld details shown in Fig. 1. The cruciform joint could be designed to fail from the weld toe, but it was used here to study fatigue fracture in the weld throat, the crack initiating at the weld root. All the specimens were 100 mm wide, and sufficiently long to enable them to be gripped in fatigue testing machines for loading axially.

The welding was performed using the MIG process for the austenitic steel and TIG for duplex, with the appropriate filler metals defined in (3).

The fatigue tests were carried out in a computer controlled servohydraulic fatigue test machine, with a load capacity of ± 250kN. The fatigue cycle was tensile loading in the main plate, with constant amplitude loading, with a sinusoidal load wave of 15-20 Hz, with stress ratios of 0.05 and 0.5. The tests were stopped when the total failure of the specimen occurred. The fatigue cracks have initiated from the weld root and propagated in the weld metal in directions close to the surface of the transverse plate. In a few specimens, the event of crack initiation was detected with strain gauges placed close to the weld toe. Results of this analysis may be found in (3). Selected fracture surfaces were inspected optically and at the SEM, to detect initial defects and to provide information concerning fatigue cracking mechanisms. Details can also be found in (3). Plots were obtained in the form of S-N curves, where the nominal stress was taken, both in the main plate and in the weld throat, and N_r was the fatigue endurance.

In order to provide a representative geometry for the model specimen, to be used in the finite element analysis, the depth of the lack of penetration in the specimens of Fig. 1 a) was measured, and the results were statistically analysed.

3. FE NALYSIS OF THE JOINT

The stress distribution and the values of the J integral at the weld root area were obtained, using the FE code ABAQUS. A linear elastic two dimensional mesh was used, with two types of isoparametric elements: biquadratic six nodes and biquadratic eight nodes with reduced integration. The lack of penetration in the weld root was simulated, like a crack or discontinuity in the material, assuming no contact forces between the elements along the discontinuity. Due to the symmetry of the joints and of the load, only one quarter of the specimen was analysed. Fig. 2 shows the typical mesh proportions with the elements chosen to obtain the stress distribution. For the computation of J integral the meshes were modified, since collapsible elements were used.

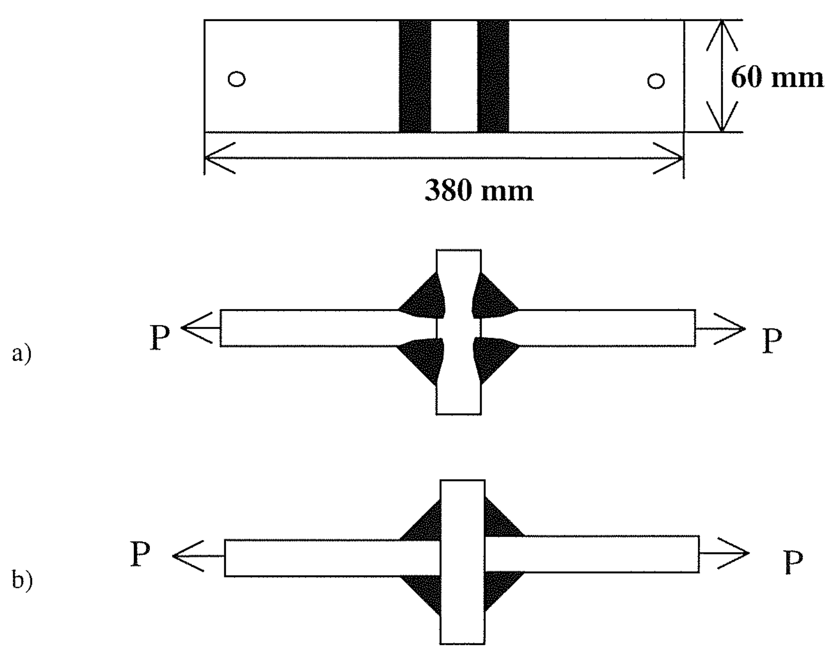

Fig. 1 – Cruciform load carrying specimens used in the fatigue tests. a) Partial penetration, 304L stainless steel.
b) No penetration, 2205 duplex stainless steel.

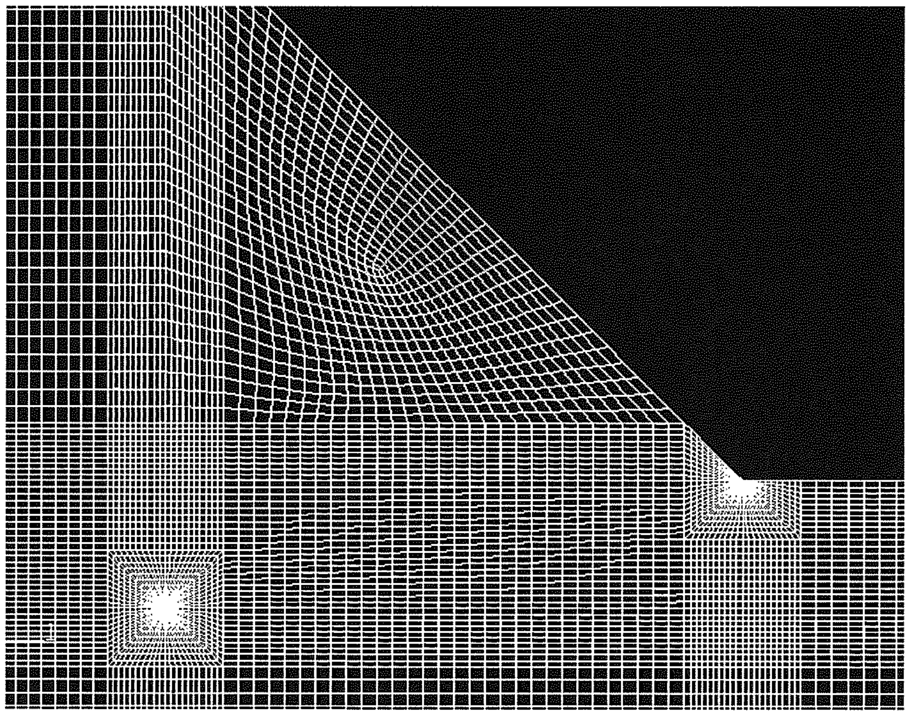

Fig. 2 – Typical mesh proportions used to obtain the stress distribution at the weld root in the partial penetration joints of Fig. 1 a).

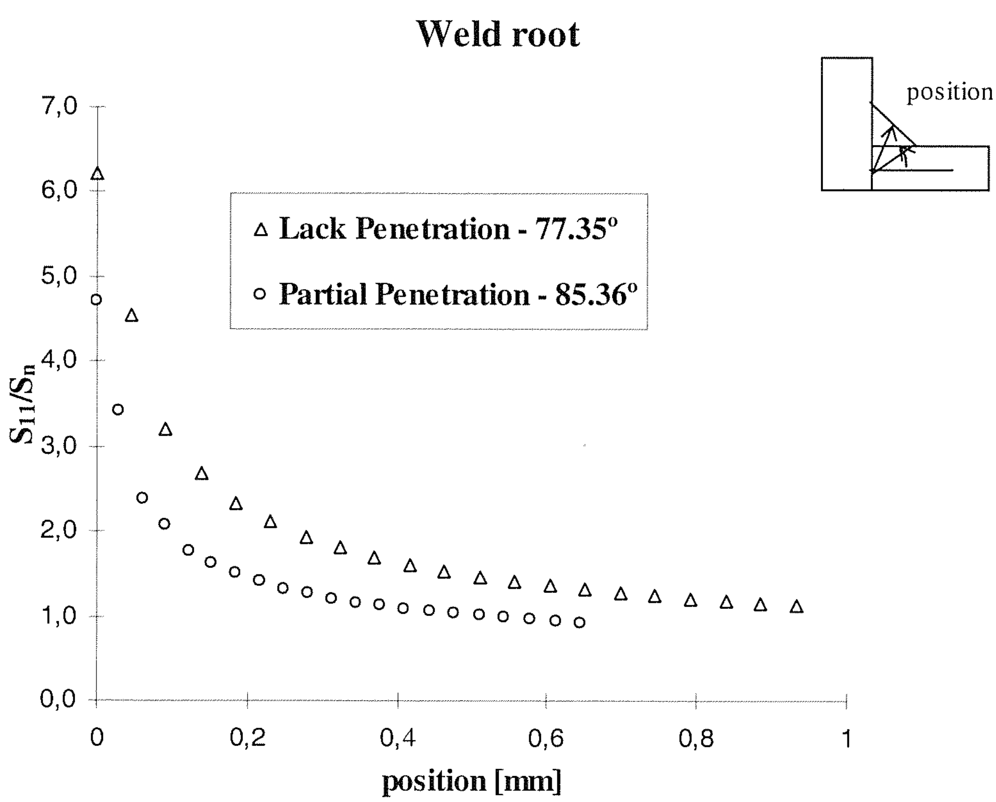

Fig. 3 – Variation of the stress concentration factor, K_t, against the polar distance, r, measured from the welded root in the directions of maximum stress. S_{11} – maximum normal stress in the loading direction, 1. S_n – nominal stress in the loading direction, 1.

The values of the stress concentration factor, K_t, at the weld root were plotted against the distance (position), measured form the weld root and along the angular directions which gave the higher values of K_t at the weld root. K_t is herein defined as the ratio of the maximum stress in the *11* direction over the nominal stress in the main plate away from the weldment. The results (Fig. 3) were obtained for the partial penetration joints (Fig. 1 a)), representative of the 304L specimens and the full lack of penetration joint of the duplex specimens where E is equal to the main plate thickness.

The highest value of K_t occurs at the weld root (e=0) (Fig. 3); $K_t \approx 6.5$ for the joint with total lack of penetration, and $K_t \approx 4.8$ for the partial penetration joints. K_t decreases rapidly as the distance away from the weld root increases, and is lower in the partial penetration joints. For $r \approx 0.7$ mm, K_t tends to one, i.e. the stress concentration effect is highly localised at the weld root zone.

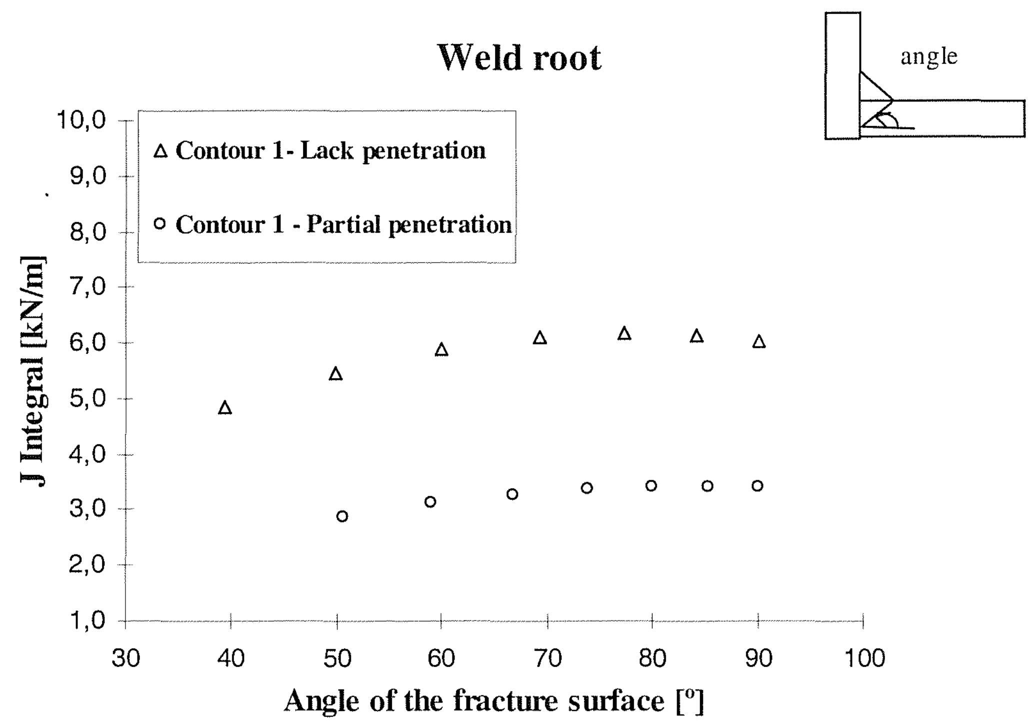

Fig. 4 – Variations of the J integral at the weld root against the angle of the fracture plane (angle of the fatigue crack).

For a nominal stress value of 100 MPa, the values of J integral at the weld root (a_i=0) are plotted against the angle of the assumed fracture plane in Fig. 4. It seems that the J integral increases as the fracture angle increases, until a maximum value is reached for fracture angles of 77.35 degrees for the local lack of penetration joints (E=B), and 85.36 degrees for the partial penetration joints.

The experimental values of the angles of the fatigue crack in the fracture surface were very close to 90 degrees, as referred before. Hence, the J integral results were able to predict the direction of fatigue crack propagation as the one that gave the maximum values of the normal stress S_{11} and of the J integral (Fig. 4).

The results in Fig. 4 also show that the values of the J integral increase by a factor of approximately 2 in the total lack of penetration joints as against the partial lack of penetration joints tested.

The cruciform fillet welded joints were fabricated with welds small enough to ensure fatigue cracking from the weld root through the throat. For such a case, design S-N curves are expressed in terms of the stress range at the weld throat rather than that in the plate (6). The present results are shown plotted in this way in Fig. 5. As will be seen, there is no significant influence of either R or the stainless steel type, and the results correlate reasonably well.

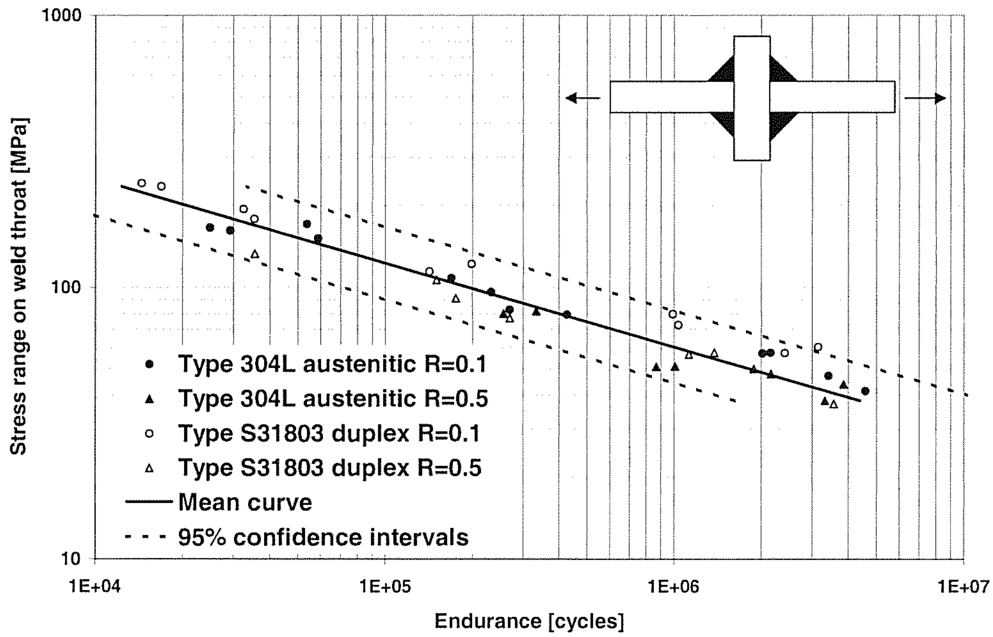

Fig. 5 – Fatigue test results for stainless steel fillet welded cruciform joints. S31803 duplex is equivalent to 2205.

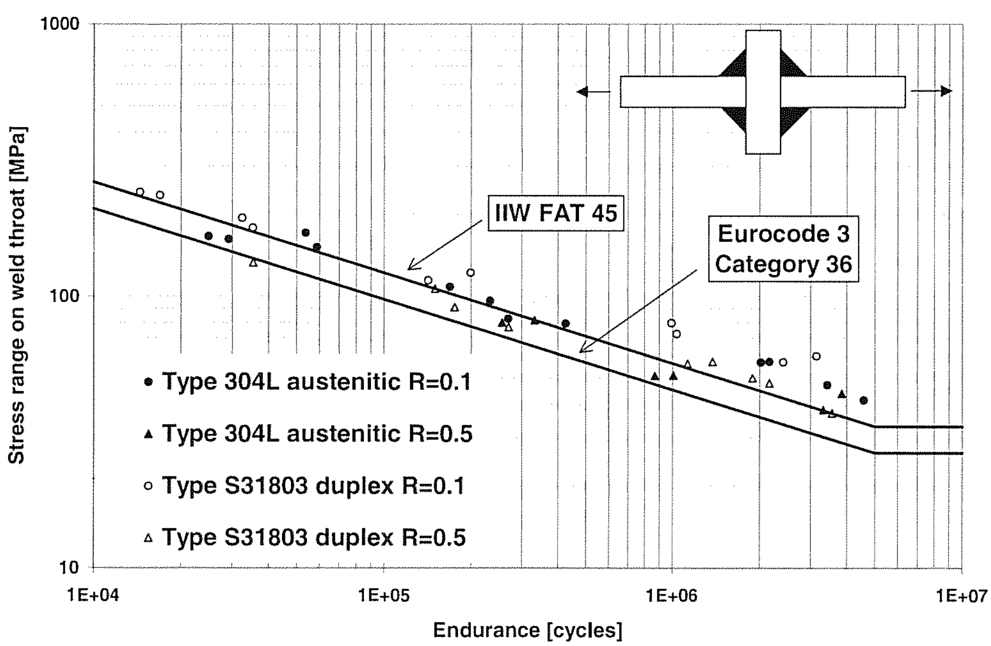

Fig. 6 – Comparison of fatigue test results for stainless steel fillet welded cruciform joints and design curves.

The tests have shown negligible initiation lives, as reported in detail in (7). This is confirmed by the fact that the slopes of the S-N curves plotted in Figs. 5 and 6 are in agreement with the experimental values of the exponent *m* of these steels.

The fatigue performance of cruciform joints in C-Mn structural steels was the subject of a detailed review recently (9). This was performed to check the design curve for weld throat failure. It was found that many data obtained since the design curve was first established fell below it.

The results are shown again in Fig. 6, in comparison with the Eurocode 3 and IIW design curves (10). The review of C-Mn steel data indicated that the Eurocode category 36 curve was the most appropriate, and the present results support this. Therefore, it is recommended that category 36 should also be used for stainless steels. However, one aspect of even that curve needs further investigation, namely the location of the fatigue endurance limit. The results (Figs. 5 and 6) indicate that the fatigue endurance limit should correspond to an endurance much higher than $5x10^6$ cycles, the maximum life obtained in the fatigue tests; choosing the stress range at 10^7 cycles seems to be a more appropriate approach, as plotted in Figs. 5 and 6.

4. CONCLUSIONS

Based on the results obtained so far in a project including both fatigue endurance tests and fatigue crack growth and threshold determination, in welded austenitic and duplex steels, some preliminary conclusions can be drawn. Clearly, these may be revised in the light of the complete results, and therefore they should be regarded as tentative. Furthermore, they refer only to fatigue test results obtained in air and should not, therefore, be assumed to be applicable for other environments.

a) A general finding was that, for a given detail, there was no difference in fatigue performance between austenitic and duplex stainless steels. This is consistent with the crack growth results obtained so far (not presented here) for the two types of steel.
b) However, it was clear that the higher strength duplex gave longer lives and stress levels above the proof strength of the austenitic steel.
c) Furthermore, in every case the present results for stainless steels fell within the scatterbands enclosing the extensive databases for the same details in C-Mn steels. However, the same may not be true in the presence of a corrosive environment.
d) Consequently, for the details tested, design S-N curves for welded C-Mn steel are equally applicable to welded stainless steels.
- The IIW design curves were generally more suitable than those in Eurocode 3.

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